Journal of Alloys and Compounds 586 (2014) S246–S249

Contents lists available at SciVerse ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Modeling of laser radiation transport in powder beds with high-dispersive metal particles

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A R T I C L E I N F O

Article history:
Available online 24 January 2013

Keywords:
Laser sintering
Radiation transfer
Light absorption and reflection
Powder bed
Computer simulations

A B S T R A C T

Two-dimensional transfer of laser radiation in a high-dispersive powder heterogeneous media is numerically calculated. The size of particles is comparable with the wave length of laser radiation so the model takes into account all known physical effects that are occurred on the vacuum–metal surface interface. It is shown that in case of small particles size both morphology of powder particles and porosity of beds influence on absorptance by the solid phase and laser radiation penetrate deep into the area of geometric shadow. Intensity of laser radiation may be described as a function corresponded to the Beer–Lambert–Bouguer law.

1. Introduction

Influence of laser radiation on powder beds is often used in many processes and we can underline among them a Selective Laser Sintering (SLS) technique. SLS allows producing complex three-dimensional parts rapidly layer wise by laser scanning a powder bed. Metal powders are highly suitable for SLS because it is impossible to produce metal parts by other rapid prototyping techniques. There are many characteristics of laser sintering process such as temperature gradient and solidification rate which influence on quality of sintered layers. It is highly complicating to choose optimal energy characteristics of the laser radiation to achieve desirable microstructure and quality of manufactured parts [1]. Thereby computer modeling of heat and mass transport can help by forecasting the temperature field and the microstructure which allow avoiding defects in sintered parts.

To the present the significant progress has been achieved in theoretical describing of interaction of laser radiation with a solid metal surface but describing of transport of laser energy in dispersive powder beds deals with well known difficulties. In case of a solid metal surface the influence of the laser radiation is considered as flow of energy on a vacuum–metal bound in a computational area but this approach is not applicable for describing laser interaction with porous powder beds. Experimental study has shown that the laser radiation due to diffraction effects penetrates deep into an area of the geometric shadow and the distribution of penetrated intensity of laser radiation may be written as [2]

$$I = I_L \exp(-\gamma h), \quad (1)$$

where γ is the extinction coefficient; h is the coordinate directed into the powder bed and I_L – intensity of laser radiation at the surface of the powder bed. It is highly time-consuming to obtain exact value of the extinction coefficient γ experimentally [2]. Main problem is an accuracy of measurements and it becomes significantly lower with decreasing of the metal particle size. So in view of large variety of powders' dispersity and types of used materials and compounds computer modeling of laser energy transport may give us a good approach to predict the extinction coefficient which is necessary for modeling of heat and mass transport during laser sintering.

Diermendjian [3] suggested the model of light energy transport in a dilute dispersive media with equations which were obtained in Mie scattering theory by considering of light diffraction on polydisperse spherical nontransparent particles. But using the model for describing of light scattering by dense dispersive media referred to considerable difficulties [4]. Other approaches based on geometric optics might be inapplicable here due to comparable values of the wave length of the laser radiation and the average diameter of metal particles. Among existing models on describing laser scattering in a dense powder media in which radiation penetrates through open pores a model of heterogeneous scattering media widely discussed in the literature [5]. But despite the fact that the model based on equation that are applicable for light scattering in dilute disperse media some coefficients of the model such as scattering coefficient σ and extinction coefficient γ are chosen by the geometric optics approach. The model is relevant to the most of powder types currently applied for laser sintering because the size of powder particles is about several tens of microns, which is much greater than a wavelength of typically used lasers for SLS of about 1 μm. Nevertheless using smaller size of powder particles in SLS processes occurs often and main goal of this study is to

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0925-8388/$ - see front matter
http://dx.doi.org/10.1016/j.jallcom.2013.01.061

establish how the extinction coefficient depends on the particles size and on its morphology by computer modeling of transport of laser radiation.

According to the study Ref. [6] composite Fe–3.2%Ni powder might be a novel effective material for rapid production of metal parts using selective laser melting (SLM) technique. Composite powder consisted from spherical particles of iron in the nickel shell. Laser sintering allows achieving parts with high resistance to corrosion. Corrosion resistance is comparable to a stainless steel with high content of chrome and nickel [6]. It is shown that under special sintering conditions sintered parts remain high content of nickel on its surface which explains high level of corrosion resistance. But achieving that property has required a careful choose of laser sintering conditions. Energy characteristics of laser radiation should be chosen to provide a non-equilibrium distribution of components after solidification close to the initial distribution in the composite powder. Computer simulation of laser irradiation of powder beds is necessary to optimize the technology of laser sintering. So the second goal of this study is to explore the characteristics of the laser energy transport in a powder bed with complex shape of composite Fe–Ni particles.

2. Model

Transport of radiation, light absorbing by metals, scattering, dispersion and diffraction of light in a media are described by the classic electrodynamics theory. Solving of the Maxwell's equations system for a homogeneous isotropic media with conductivity σ leads to an equation

$$\nabla^2 \vec{E} - \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} - \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0. \tag{2}$$

This equation is named the telegraph equation and its solution is a damped wave which can be described by an equation with production of two independent parts:

$$\vec{E} = \vec{U} \cdot \exp[-i\omega t], \tag{3}$$

where $\vec{U}$ is the coordinate part of solution independent from the time variable. Substituting the solution (3) into Eq. (2) results in the equation for an isotropic continuum

$$\nabla^2 \vec{U} + k^2 \vec{U} = 0, \tag{4}$$

which is the Helmholtz equation and it describes waves propagation in elastic mediums, where k is the wave number. The wave number is a real number for wave propagations in the vacuum ($k = 2\pi/\lambda$, where λ is the length of light wave) and a complex number for propagation in a conductive media (e.g. in metals). So instead of solving the dynamic Eq. (2) it is possible to obtain solution from the steady state Helmholtz equation which is applicable here due to the fact that distribution of light energy in media is possible to be considered as a quasi-steady-state almost from the beginning to the end of the impulse especially in a case with low energy of impulse.

Eq. (4) is valid for every points of the modeling area except for the metal/vacuum interface where characteristics of media and consequently electromagnetic waves are deeply changed. Boundary conditions for the vacuum/metal interface might be received from the integral Maxwell equations. But action of light on metal surfaces is well described in the literature and leads to reflection of light with reflection coefficient R and penetration of the radiation into the metal media. Penetrated part of the radiation extinct very intensively due to high conductivity of metals so depth of layer where radiation is almost absorbed (skin-effect) is about several nanometers. So we can exclude processes of light extinction in metal particles from considering and take into account only reflected radiation on the vacuum/metal solid interface. In this case the boundary condition on the metal interface is

$$\vec{n} \cdot \vec{\nabla} U + ikU = \frac{2ik\sqrt{R}Ue^{-i\pi}}{1 + \sqrt{R}e^{-i\pi}}, \tag{5}$$

where reflected wave meets with the phase shift by angle of π radians which is correspond to half length lose phenomenon under light reflection from a media with higher optical density. Boundary condition for a source of light is

$$\vec{n} \cdot \vec{\nabla} U + ikU = 2ik, \tag{6}$$

for full absorption ($R = 0$)

$$\vec{n} \cdot \vec{\nabla} U + ikU = 0 \tag{7}$$

and for mirror reflection without phase shift ($R = 1$)

$$\vec{n} \cdot \vec{\nabla} U = 0. \tag{8}$$

3. Results and discussion

2D numerical modeling of laser energy transport was performed both for simulative powder beds and for a powder bed which parameters corresponds to a physical experiment described in [2]. Parameters for simulation are listed in Table 1. Laser radiation with wave length 1.065 μm enters to a powder bed through the upper boundary.

Simulative powder beds were composed from identical spherical particles incidentally placed in the computational area. Simulations were performed for powder beds with different radius of particles and packed densities in order to establish the influence of these both parameters on extinction of laser intensity.

Numerical model was implemented using commercial computational package Comsol Multiphysics 3.5a, which is suitable for solving of engineering and physical tasks. Steady-state Eq. (4) was realized by finite-element method using Comsol facilities. Geometry of the computational area and the computational grid close to the surface of a metal particle are shown in Fig. 1. The shape of the particle corresponds to the real particle's shape of the Fe–Ni composite powder [2]. The composite powder was obtained using technique cited in paper [7]. All computations were performed in 2D area so the spherical particles were represented by infinite cylinders with a circle at the base. Each of circles has diameter d. In this case the density of the powder beds is calculated as a relation between the space occupied by circles and whole space of the computational area. Computational grid is made from triangle shaped elements.

Boundary conditions: boundary Ω_1 corresponds to the source of electromagnetic waves with the amplitude of one relative unit (6); on boundaries Ω_2 occurs mirror reflection according to Eq. (8);

Table 1
Simulation conditions.

Simulative powder beds:	
Radius of spheres (μm)	1, 2, 3, 4, 6, 9, 12
Packed densities (%TD)	5, 12, 20, 28, 36, 48, 60
Powder bed from experiment [2]:	
Particle size (μm)	0.5–4
Average particles size (μm)	3
Packed density (%TD)	28
Chemical composition	Fe–3.2 wt%Ni
Reflection coefficient	$R_{FE} = R_{Ni} = 0.7$
Calculation area:	
Geometry (μm)	30 × 50
Maximum mesh size (μm)	0.1
Number of nodes	10^6